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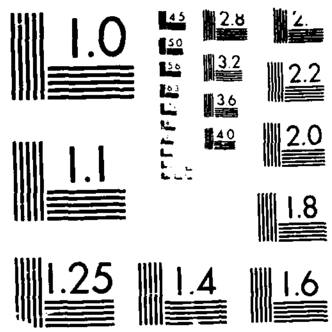

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Local Free-Space Mapping and Path Guidance for Mobile Robots

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This work was conducted by the Autonomous Systems Branch (Code 442) of the Naval Ocean Systems Center between April 1986 and October 1986. The algorithms were specifically developed to handle acoustic sensor data for the Ground Surveillance Robot, though they can be used for any robot, and for data from other than acoustic sensors. The authors would like to thank Scott Harmon, Doug Gage, Walter Aviles, and Guy Bianchini for their assistance in developing the algorithms and in reviewing the paper.

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A method was developed of mapping the local environment in front of a ground vehicle that employs acoustic sensors. The extent of known free space is used to generate navigation points, in the form of a subgoal and avoidance points, which may be used by another process to generate a path. The map information is also used to steer the sensors to areas of the environment that require further investigation. Inconsistencies in sensor returns are resolved with multiple sensor scans.

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INTRODUCTION

Autonomous mobile robots must be able not only to sense their environment, but also to navigate through it, avoiding obstacles and heading in the general direction of some goal. To this end, the more intelligent robot can accumulate the sensor data into a local map from which a path towards a goal can be determined. Understandably, mapping the robot environment from sensory information has generated a great deal of interest.

There are currently two basic methods of storing information used in mapping an environment. One method represents the environment as a grid of squares, with square dimensions possibly ranging from 0.5 by 0.5 feet (Ref. 1) to 3 by 3 meters (Ref. 2). The squares can be defined by discrete entities, such as "occupied," "free space," or a specific terrain type (Ref. 3, 4); by graded values which represent probabilities of being occupied (Ref. 5); or by both discrete entities and graded values (Ref. 1). The advantage of the grid method of map storage is its ease of generation and updating. Each square of the grid has some value which, as new information comes in, can be replaced or mathematically averaged. It is difficult, however, to analyze the paths to a goal when such a method is used because the environment is not represented as an integrated whole.

Another method of storing map information uses line segments to define object or free-space entities (Ref. 6 through 10). These segments can even be generated from the grid-type map (Ref. 2). Associated with each segment may be one or both end points, entity (object or free space), probability of entity, or other mathematical functions useful in future analysis for path planning. The disadvantage ot this method of map storage is the difficulty in updating the map. Is the segment generated from new sensor data a new segment or the repetition of an already existing segment in the map structure? If it is new, how should it be integrated with the existing segments? And if it is a repetition, how should the new information on this segment be integrated with the old information? The advantage of this method of mapping over the grid-storage method is that the obstacle and free-space regions are defined in such a way that makes it easier to generate paths.

In this report, the line-segment method of map representation is used. This eases the task of generating a subgoal and avoidance points used in navigating toward a goal. By reducing the map to a subgoal and avoidance points, the amount of information passed to a path planner is dramatically decreased, allowing for the easier fusion of sensor data. The line-segment map representation developed in this report distinguishes itself from other approaches in that it maps free space and not obstacles. This report describes the algorithm used to incorporate new sensor data with the existing collection of line segments. It also shows how this new map is used to generate a subgoal and appropriate avoidance points to be used by a path planner and to move sensors to scan relevant areas of the environment.

DESCRIPTION OF ROBOT SYSTEM

The mobile robot used in this study is the Ground Surveillance Robot (GSR) described in Ref. 11 and shown in Fig. 1. Briefly, this vehicle is an M114 Armored Personnel Carrier with sensors that monitor vehicle attitude and environmental terrain. The vehicle is designed to traverse unknown terrain to a given goal while avoiding obstacles. The mapper described here uses data from the acoustic range finders, but the principles upon which the mapper is based can be applied to other sensory information.

Figure 2 shows the GSR system architecture. It consists of independent modules, each communicating through an Intelligent Communications Interface (ICI) (Ref. 12) across a shared local area communications network. The vision/laser range finder module provides environmental information at far ranges, leaving the near range (within 10 meters) to be covered by the acoustic sensor module. A far-range goal is generated by a planning module. The acoustic sensor module's task is to map the immediate environment and generate a subgoal based on the mapped free space and the known location of the far-range goal with respect to the vehicle. This subgoal is the desired position for the vehicle within this immediate environment. In addition, avoidance points are generated based on detected free-space edges (obstacles). The subgoal and avoidance points are passed to a locomotion module, which controls the vehicle throttle, braking, and steering. A navigation module provides vehicle position, heading, and speed, all of which assist in moving the vehicle through the environment away from avoidance points and toward the subgoal. Thus, an explicit path is not generated by the acoustic sensor module, but instead is generated dynamically by the locomotion module from the subgoal and avoidance points.

Seven Polaroid acoustic sensors are mounted on the front of the vehicle, as shown in Fig. 1. The three sensors mounted at the center of the vehicle are fixed in position, 15 degrees apart, resulting in a cumulative beam width of the three sensors (assuming an individual beam width of 15 degrees) of 45 degrees centered around the vehicle's dead-ahead axis. Two steered sensors are mounted on each side of the vehicle's front and can be steered to any position between ±75 degrees from dead ahead within 20 ms. These are "time of flight" sensors and measure the time for an acoustic wave to travel out to an object and reflect back. The distance to an object is determined from this time and the speed of sound and is called the sensor's return. The maximum range of the sensors is 10 meters. Beyond this distance, any reflected acoustic wave is too weak to sense reliably.

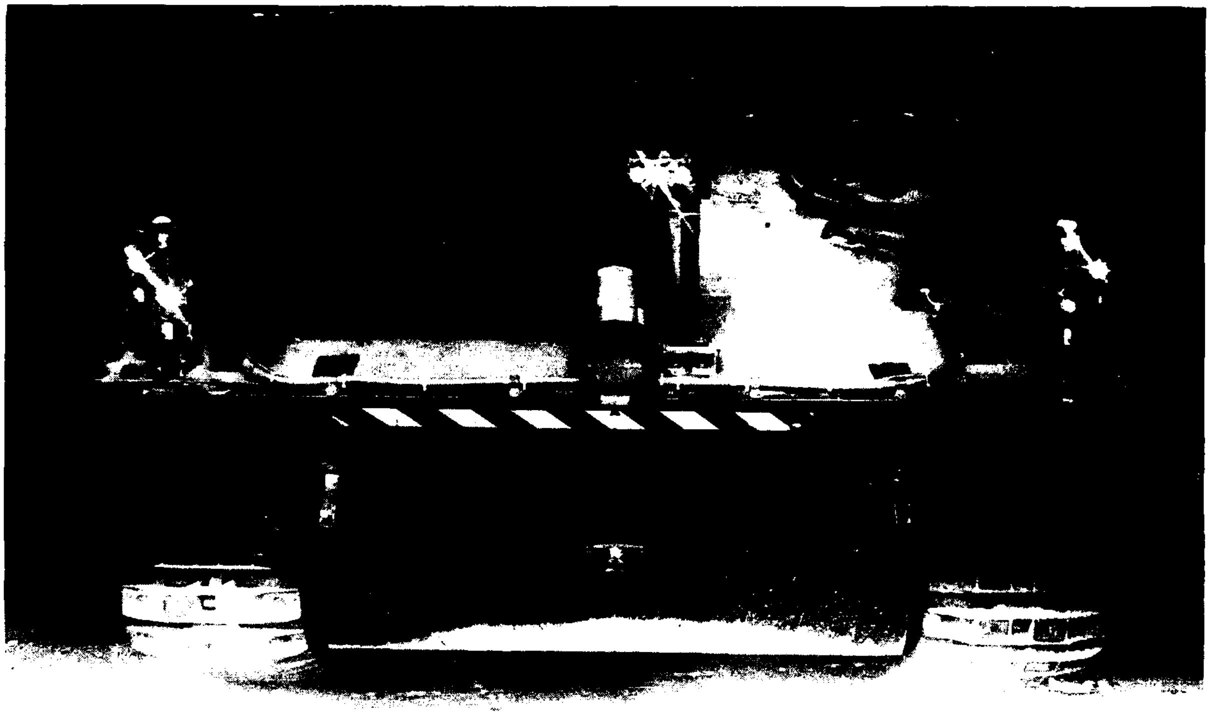

Figure 1. Ground Surveillance Robot.

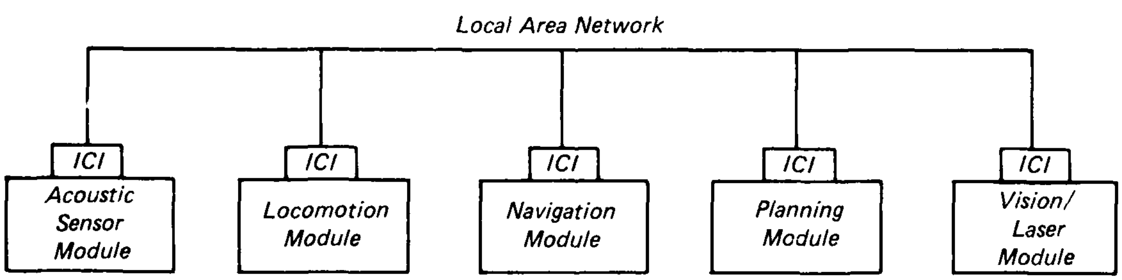

Figure 2. GSR system architecture.

FREE-SPACE MAPPING

MAP CONSTRUCTION

The mapper program creates a boundary of line segments that outlines the extent of known (by the acoustic sensors) free space. This boundary consists of an exterior boundary, which reaches out to the limit of the acoustic sensors (10 meters), and interior boundaries, which represent areas that are either unmapped or show an object and which are completely surrounded by identified free space. The exterior boundary and each interior boundary is represented by an array of line segments. Each segment has associated with it --

(1) the x,y location of the segment's right-most (as seen from the vehicle) end point in absolute coordinates

(2) the sighting (e.g., free space or object)

(3) the slope and y-intercept of the segment with respect to the absolute coordinate frame

(4) the direction in which the line segment should be traversed to keep known free space on the left-hand side

The mapper takes range information from the sensor and creates a triangle to represent the acoustic cone dispersion in two dimensions, with the sensor location as one vertex. (The error associated with this approximation of the arc by a straight line is less than 1%.) The interior of the triangle is known to be free space. The edge opposite the sensor vertex represents the only legitimate sighting, which can be either "object" if a sensor return of less than 10 meters is measured, or "free space" if no object is detected within the reliable range of the sensor. If the sighting is object, then an object exists somewhere along that segment. Owing to the dispersion of the audio signal, the exact location of the object is unknown, so the entire area of the segment and beyond is considered object until future returns redefine it with free-space sightings. The edges of the triangle adjacent to the sensor position are called "radial" segments; they have no legitimate sighting (free space or object) associated with them.

The union of the free space inside the sensor triangle (new data) with the existing free-space boundary creates the updated free-space boundary. To determine the triangle of the new sensor data, the vertices of the triangle are first determined in absolute coordinates by using absolute vehicle position and heading and (with respect to the vehicle) relative sensor position, heading, and return. Then the triangle segment's slopes and y-intercepts are calculated with respect to an absolute origin.

All intersection points between each triangle segment and existing boundary segments are then determined by using the slope and y-intercept representation of each segment. Each intersection point has associated with it --

(1) the absolute x,y position of the intersection

(2) the intersecting segment of the boundary

(3) the intersecting leg of the triangle

(4) the order of the occurrence of the intersection point on the boundary (from right to left on the exterior boundary and clockwise on the interior boundary)

(5) the order of the occurrence of the intersection point on the triangle (counterclockwise, beginning at the sensor vertex)

The new exterior boundary is formed by tracing the existing boundary from right to left. (This tracing is shown in Fig. 3 and is discussed in the next section.) This keeps the known free-space region always on the left-hand side of the traced boundary. (The choice of right to left is arbitrary; the tracing could be done from left to right, with free space located on the right-hand side.) When an intersection point is encountered while tracing the existing boundary, the new boundary follows the right-most segment (either old boundary segment or new triangle segment) to the next intersection point, where the procedure is repeated. Tracing the new boundary is continued, and the right-most path is followed until the last point in the old exterior boundary structure is reached. The right-most path is used in order to expand the known free-space boundary into unknown territory as much as possible. This procedure will create new boundary segments and delete old ones, though the majority of old boundary segments will remain unchanged, since the union of new sensor data with the existing boundary usually creates small additional free space. As segments fall behind the vehicle because of its forward movement, they are deleted from the map.

MAPPING EXAMPLES

Figure 3 shows the procedure for updating the existing boundary. Two intersection points (P and Q) are found in the union of the old exterior boundary with the new sensor data. Intersection point P is associated with segment $\overline{67}$ of the old boundary and segment $\overline{AB}$ of the new sensor data, while intersection point Q is associated with segment $\overline{67}$ of the old boundary and segment $\overline{CA}$ of the new sensor data. The new boundary is formed by tracing the old boundary

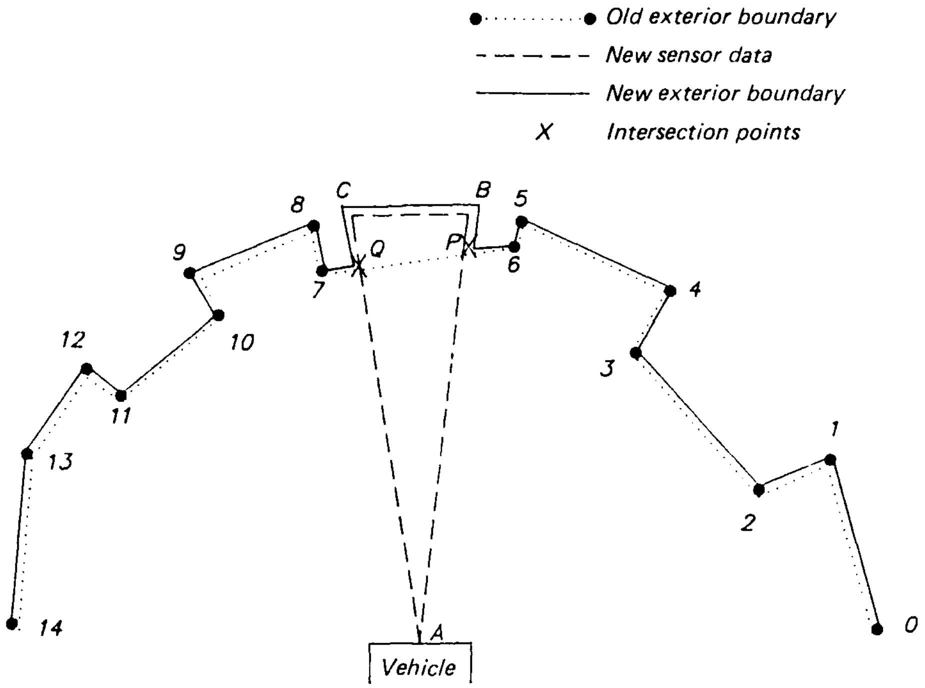

Figure 3. Updating exterior boundary.

from point 0 through point 6 and to the intersection point P. The right-most segment at intersection point P is the top portion of triangle segment $\overline{AB}$ (segment $\overline{PB}$). Therefore from intersection point P, the new boundary is traced along the segment $\overline{PB}$. Triangle segments $\overline{BC}$ and $\overline{CQ}$ are then followed until intersection point Q is encountered, at which time a new decision is made. Since the segment $\overline{Q7}$ is more right than the segment $\overline{QA}$, the segment $\overline{Q7}$ is chosen as the next segment on the new boundary. Since there are no more intersections, the new boundary continues following the old boundary segments until the end point, point 14, is reached.

During this process of determining the new boundary, the next intersection point on the exterior boundary is checked to see if it is also the next intersection point on the triangle. In Fig. 4, the new boundary follows segment $\overline{PB}$ from intersection point P. However, the next intersection point on the existing exterior boundary (Q) is not the same as the next intersection point on the triangle (S). When this occurs, a new interior boundary is created, and the segments are traced clockwise until a triangle segment can close it up. In Fig. 4, the interior boundary traces segments $\overline{QE}$ and $\overline{ER}$ before finding segment $\overline{RQ}$ to close it. The next intersection point on the exterior boundary (S) is then checked to see if it is the next intersection point on the triangle before the interior boundary was formed. Since in this example it is, the new exterior boundary continues from the last intersection point P and traces segments $\overline{PB}$, $\overline{BC}$, and $\overline{CS}$ before tracing the remainder of the existing exterior boundary.

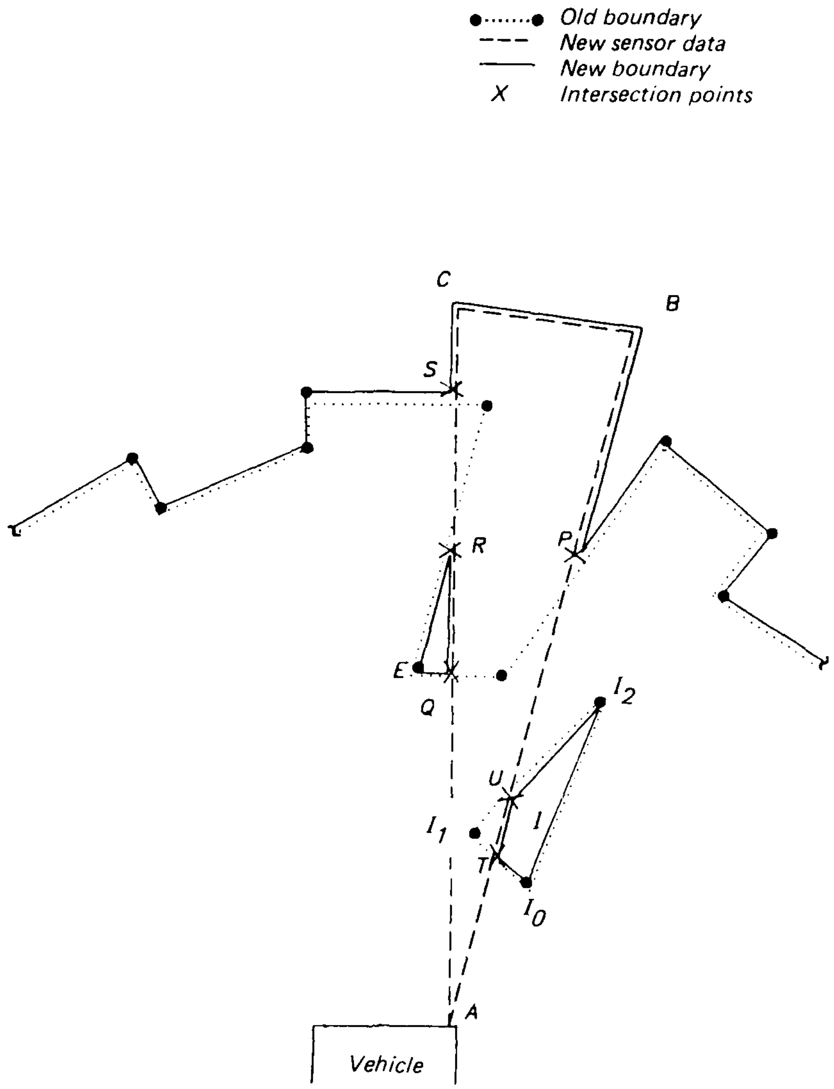

Figure 4. Creating and updating interior boundaries.

The existing interior boundaries are examined for intersections with the new sensor data. If intersections occur, the interior boundary can be updated. In Fig. 4, interior boundary I is intersected twice. It is traced clockwise, beginning at point I_0, until intersection point T is encountered. Again, the right-most path is chosen to cut into unknown space as much as possible and segment $\overline{TU}$ becomes the second segment of the interior boundary I. The procedure continues until the beginning point of the interior boundary is reached. (Segments $\overline{UI_2}$ and $\overline{I_2I_0}$ become the third and fourth segments, respectively.) During this procedure, additional interior boundaries may also be created (e.g,. an interior boundary may be split into two interior boundaries).

Each interior boundary is also checked to see if the new sensor data eliminate the interior space (i.e., there are no intersections and the entire interior boundary falls inside the triangle). If so, that interior boundary's array of line segments is deleted.

SENSOR UNRELIABILITY

The acoustic sensors occasionally report false positive returns (an object is detected that does not exist) and false negative returns (an existing object was not detected). Others (Ref. 1,5,6,9) have handled this sensor unreliability by associating with each point or segment in the map some probability that the data are correct. Consistent sightings in one area will increase the probability that the sighting is correct, while intermittent sightings will reduce the probability. When the map is analyzed for paths to a goal, these probabilities must be taken into account by picking the path that has the most likelihood of being traversible.

In this report, the approach taken to the sensor unreliability problem is to define a map which if in error, errs on the side of safety, while resolving any potentially dangerous inconsistencies by making multiple sensor scans. Therefore, while the map may be temporarily in error, the complexity of analyzing a map containing "fuzzy" segments is avoided.

For example, if the new sensor data report an object that is inside an area that was previously mapped as free space, one of three explanations is valid:

(1) The previous free-space reporting was erroneous (false negatives).

(2) The new-object report is erroneous (false positive).

(3) The environment is dynamic (moving objects).

The most dangerous response to such an inconsistency is to ignore the new-object report. Therefore, the new boundary map incorporates this new-object segment by projecting the triangle's radial segments beyond the object segment until they intersect the existing boundary segments (see Fig. 5). The new boundary traces these projected radial segments and the object segment between the intersection points. Otherwise the boundary remains the same. If the new data report is in fact a false positive, the only penalty is that a path may be planned around an object that does not exist. Future returns from that area should indicate free space, and the false positive will eventually be erased, perhaps before the vehicle takes unnecessary detours.

If the new sensor data completely erase a preexisting-object segment, again, three explanations are possible:

(1) The previous object sighting was erroneous (false positive).

(2) The free-space reporting is erroneous (false negative).

(3) The environment is dynamic (moving objects).

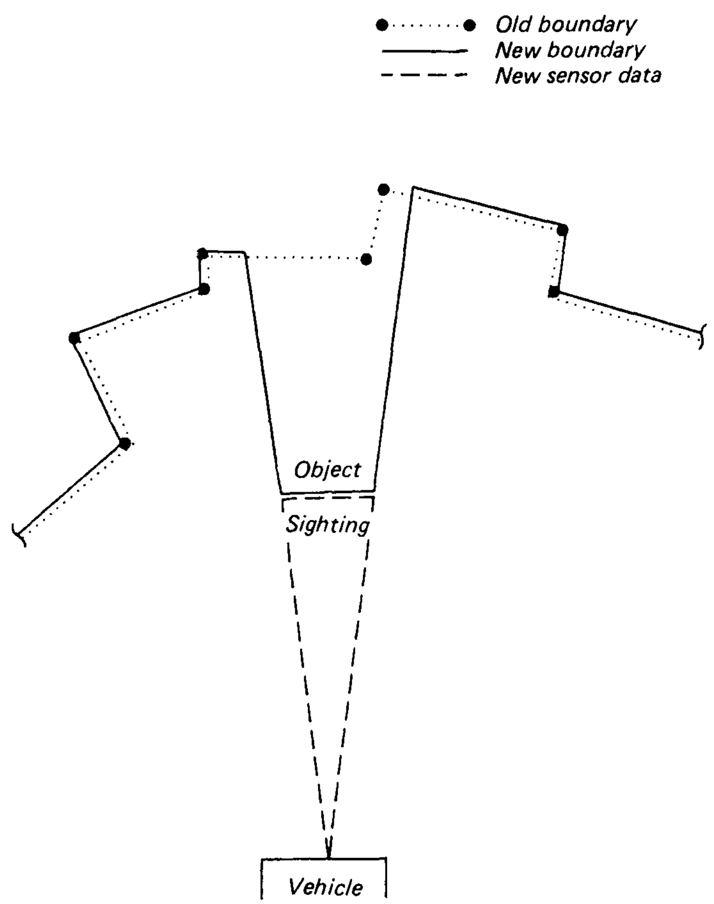

Figure 5. Handling sighting inconsistencies.

In this case, the most dangerous response is to ignore the previous object sighting. Therefore, the object is not ignored when subgoal and avoidance points are determined until four different sensors (if possible) have checked the area in question. This is accomplished by preventing the communication of subgoal and avoidance-point positions to the locomotion module until the four new sensor returns are analyzed. The mapper erases the object segment in question from the map while directing four sensors to the area. Each return that comes in is then integrated into the map as usual. If the object did exist and was erroneously erased, it will be returned and incorporated into the map as described above. After the four returns have been analyzed, new subgoal and avoidance-point positions are calculated from a presumably correct map and are communicated to the locomotion module. If while one conflict is resolved, another conflict arises, the locomotion module is told to stop until all conflicts are resolved.

PATH GUIDANCE

GENERATION OF SUBGOAL

After the new map is generated, the subgoal is determined. The subgoal will always be located within (or on the edge of) the space mapped by the sensors. The choice of subgoal is dependent on the contents of the immediate environment and the location of the goal. A hierarchy of possible choices exists, from the most direct route to the goal to more roundabout routes when the direct route is unavailable.

The first choice for a subgoal (SG) is directly along the line between the vehicle center (V) and the goal (G) (see Fig. 6). The intersection of this line with the exterior boundary is found. If the intersection is with a free space or a radial segment, then the intersection point is saved as a possible SG. The segments around the intersection point are examined to determine if the opening through the boundary is wide enough to accommodate the vehicle (i.e., there are no nearby object segments). If the opening is wide enough, the intersection point becomes SG.

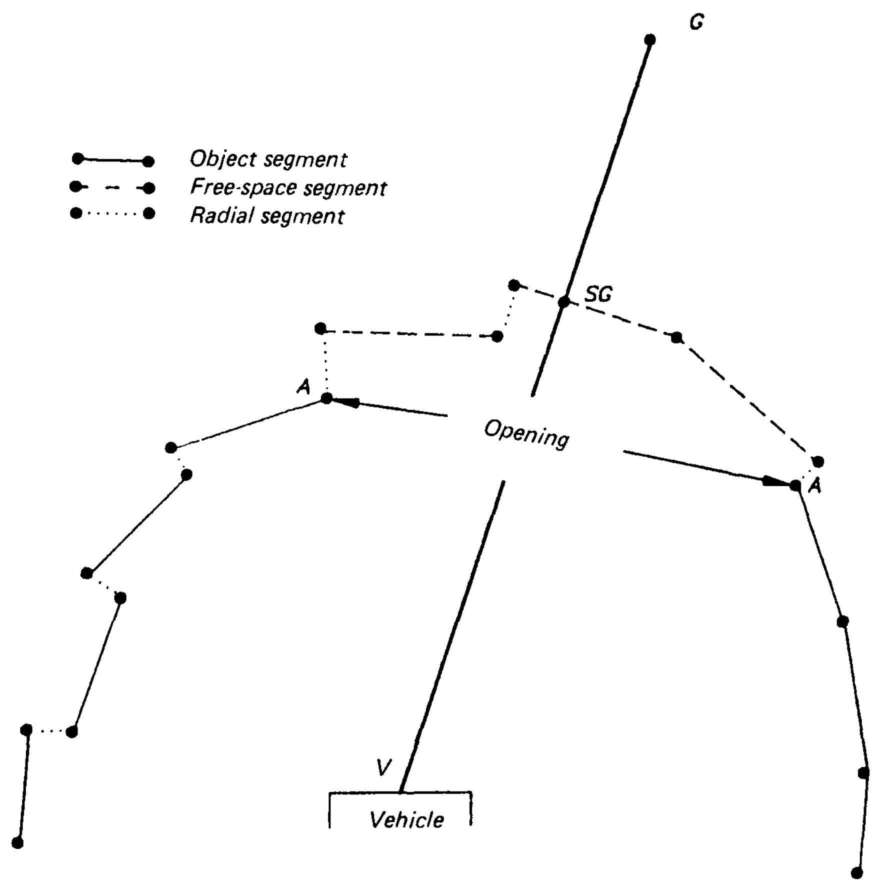

Figure 6. Direct path to goal.

If this opening in the exterior boundary is not wide enough, or the intersection is with an object segment, the next choice for SG is on a free-space section of the exterior boundary on either side of segment $\overline{VG}$ (see Fig. 7). Free-space sectors (contiguous free space and radial segments) are first examined to see if their width is wide enough for the vehicle to pass. The free-space sector with such an opening that is closest to segment $\overline{VG}$ is chosen to be the subgoal sector. If no free-space sector is wide enough, the subgoal sector is the widest free-space sector within a certain angle (currently $\pm$30 degrees) of segment $\overline{VG}$. If no free-space boundaries exist within this angle window, then the free-space boundary outside this window that is closest to segment $\overline{VG}$ is chosen as the subgoal sector.

Given a subgoal sector from free-space boundaries, a point is selected along the line connecting the start (S) and end points (E) of the sector. This point bisects the line if the opening is less than the vehicle safety width (the width of the vehicle plus a safety margin, currently about one-third of the vehicle width). If the opening is greater than the vehicle safety width, the point is chosen at one-half of the vehicle safety width from the end point closest to segment $\overline{VG}$. A line is then drawn between this point and the vehicle center. SG becomes the intersection of this line with the exterior boundary. Figure 7 exemplifies the determination of SG when the map contains one free-space sector that is not in the direct path between vehicle and goal. Segment $\overline{SE}$ represents the line between the start and end points of the free-space sector. Point X represents the intersection point a distance (d) of one-half of the vehicle safety width from the end point closest to segment $\overline{VG}$.

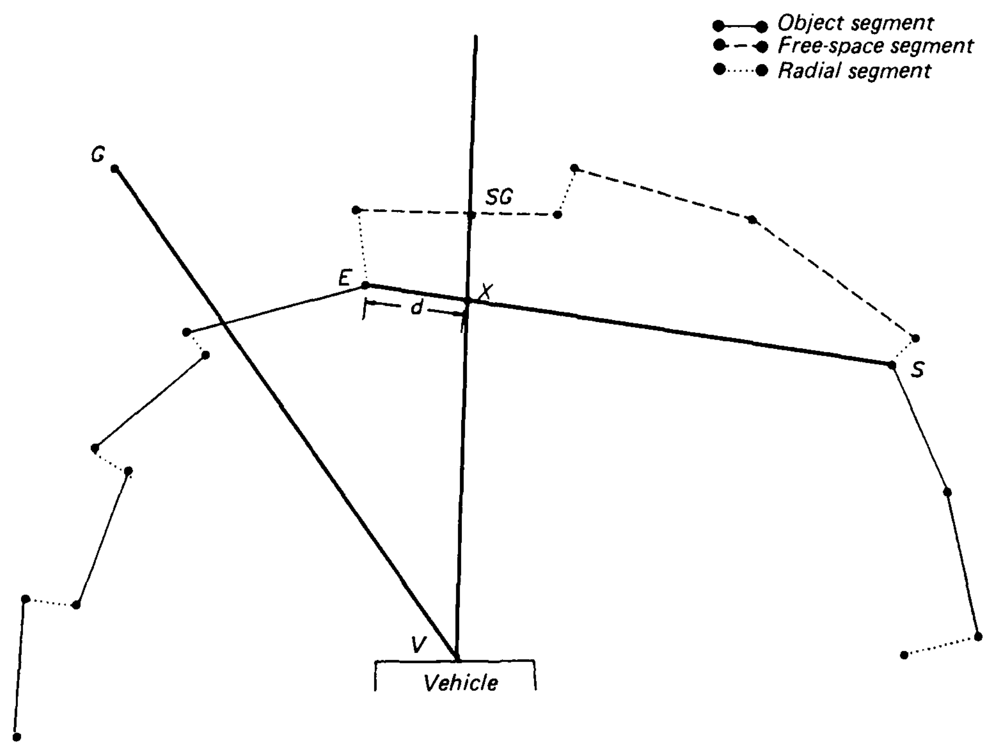

Figure 7. Indirect path to goal through free-space sector.

If there are no free-space boundaries in the current map, the next choice for the location of SG is in a long radial segment, since radials represent unexplored territory that might be free space. (Long radials are radial segments or series of contiguous radial segments that are at least as wide as the vehicle safety width.) The largest long radial is chosen for the location of SG. Long radials outside an angle window (currently ±30 degrees) are weighted by the angular distance between segment $\overline{VG}$ and the line between the vehicle center and the closest radial endpoint. A point is found which bisects the chosen radial segment. A line is then drawn between this point and the vehicle center, and SG becomes the intersection of this line with the exterior boundary. Figure 8 shows a map with no free space and only one contiguous radial segment large enough to accommodate the vehicle. The point X marks the bisection of the opening of the radial space.

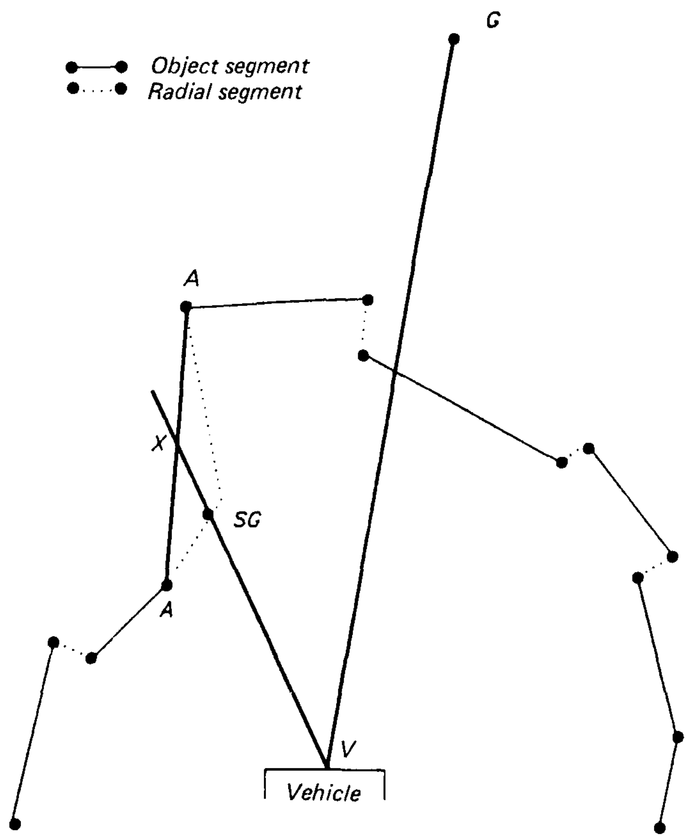

Figure 8. Indirect path to goal through radial segments.

If there are neither free-space boundaries nor long radial segments, SG is chosen as the end point of an object segment that is farthest from the vehicle. The hope is that as the vehicle continues to move forward, an opening will be detected by the sensors. Distances between the vehicle and the object segment end point are weighted when the object lies outside the angle window, as described previously. This situation is depicted in Fig. 9.

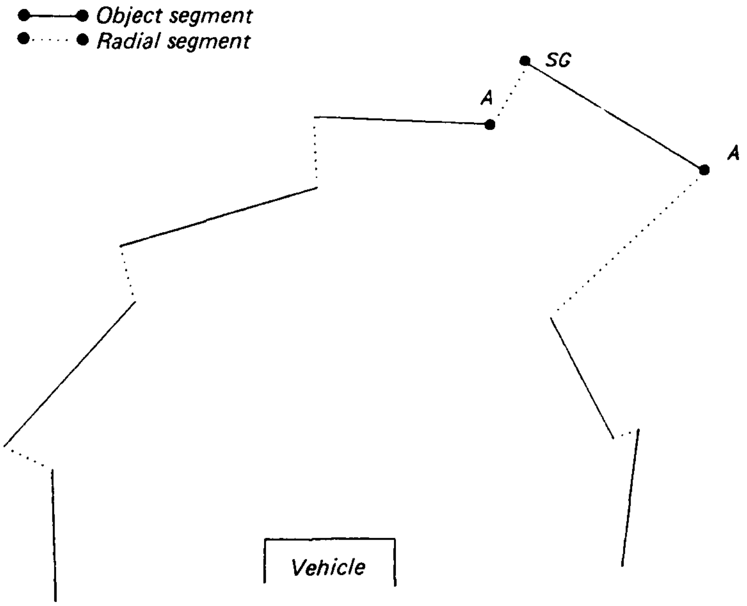

Figure 9. Vehicle surrounded by objects.

GENERATION OF AVOIDANCE POINTS

Once SG is found, new avoidance points (A) are selected as--

(1) the end points of the opening along the direct route (see Fig. 6)

(2) the end points of the subgoal free-space sector (points S and E in Fig. 7)

(3) the end points of the long radial segment (see Fig. 8)

(4) points on either side of the farthest object point (see Fig. 9)

Each interior boundary also has associated with it an avoidance point, selected as the point closest to the path to SG. Old avoidance points (from previous subgoals) are repositioned or removed as the map is updated.

INTELLIGENT SENSOR MOVES

Map information, along with the determination of subgoal and avoidance points, is used to move the steered sensors to areas of the environment that require further investigation. Several types of moves are currently employed. The two inside steered sensors are periodically moved to scan the area immediately adjacent to the -22.5-degree to +22.5-degree field of view of the fixed sensors, to cover blind spots in front of the vehicle. Steered sensors are also directed to scan interior boundary avoidance points to further delineate the interior object. The sensors will examine the direct path between the vehicle and the goal to determine if a more direct route is possible. They will also periodically search long radials which represent unmapped regions. And finally, the steered sensors are asked to verify potentially false negative and false positive reports, as described earlier.

FUTURE WORK

The determination of subgoal and avoidance points in this report has not taken into account the possibility that the vehicle may not be able to get to the designated subgoal. For example, interior objects or a convoluted exterior boundary may be in the path between the vehicle and the subgoal. Or the opening between interior objects and a convoluted exterior boundary may be too narrow to allow vehicle passage to the subgoal beyond. The designation of avoidance points should guide the locomotion module in selecting a passable route, but a better approach would be to verify that the selected subgoal is reachable. If the subgoal is not reachable, a closer subgoal should be selected that is reachable. This can be done by reiteratively checking the direct path between the vehicle and the proposed subgoal for non-free space within the swept width of the vehicle. If non-free space exists within this area, another subgoal should be selected. The final subgoal reported to the locomotion module is then guaranteed to be reachable in a direct manner. Only the turning radius of the vehicle is not considered in subgoal selection, though this too can be added in the process of checking for a reachable subgoal.

CONCLUSIONS

The unique characteristics of this method of mapping local free space and then determining navigation points (subgoal and avoidance points) are that it--

(1) "sharpens the picture" of local terrain with each sensor fire

(2) steers its sensors to probe areas of interest

(3) reduces large amounts of information in the map to a few points for navigation purposes

Each of these characteristics contributes to the robot's capability of traversing unknown terrain in real time.

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